FINAL TECHNICAL REPORT

Project Title:

CHARACTERIZATION OF BLIND SEISMIC SOURCES IN THE MT. DIABLO-LIVERMORE REGION, SAN FRANCISCO BAY AREA, CALIFORNIA

Recipient:

William Lettis & Associates, Inc.
1777 Botelho Drive, Suite 262
Walnut Creek, California 94596

Principal Investigator:

Jeffrey R. Unruh
William Lettis & Associates, Inc., 1777 Botelho Dr., Suite 262, Walnut Creek, CA 94596
(ph: 925-256-6070; fax: 925-256-6076; e-mail: unruh@lettis.com)

Program Elements:

II: Earthquake Occurrence and Effects

U. S. Geological Survey
National Earthquake Hazards Reduction Program
Award Number 99-HQ-GR-0069

March 2000

CHARACTERIZATION OF BLIND SEISMIC SOURCES IN THE MT. DIABLO-LIVERMORE REGION, SAN FRANCISCO BAY AREA, CALIFORNIA

Author: Jeffrey R. Unruh

Affiliation: William Lettis & Associates, Inc., 1777 Botelho Dr., Suite 262, Walnut Creek, CA 94596 (ph: 925-256-6070; fax: 925-256-6076; e-mail: unruh@lettis.com)

ABSTRACT

This study presents new data and analyses to characterize a blind thrust fault beneath Mt. Diablo anticline, eastern San Francisco Bay area, as a potential seismic source. Mt. Diablo anticline is the largest contractional structure in a belt of right-stepping, *en echelon* folds and thrust faults formed in a restraining stepover between the dextral Greenville and Concord faults. Based on construction of preliminary balanced cross sections, Unruh and Sawyer (1997) interpreted that Mt. Diablo anticline is an asymmetric, southwest vergent fault-propagation fold developed above a blind, northeast-dipping thrust fault. Stratigraphic relations in the Tassajara Hills southwest of Mt. Diablo suggest that most, if not all, of the fold growth has occurred in the past 5 Ma. Based on estimates of total horizontal shortening across Mt. Diablo anticline, Unruh and Sawyer (1997) proposed that the long-term average slip rate on the blind thrust fault may be as high as 7 mm/yr. This estimate was based, in part, on the assumption that antiformal relief on Cretaceous and Eocene strata across the fold is entirely due to late Cenozoic growth of Mt. Diablo. New data obtained from exploration wells and apatite fission-track analysis for this study show that substantial structural relief existed on pre-Neogene strata prior to late Cenozoic growth of Mt. Diablo anticline. By constructing new balanced cross sections that honor independent constraints on subsurface structure and maximum rock uplift during folding, the revised maximum reverse slip on the blind Mt. Diablo thrust fault is 8 km, which is lower than the previous maximum slip estimate of Unruh and Sawyer (1997). If folding began between about 6.2 Ma and 3.3 Ma, then the long-term average slip rate on the Mt. Diablo thrust fault is about 1.3 mm/yr to 2.4 mm/yr. The modern slip rate could be faster than 2.4 mm/yr if shortening began after 3.3 Ma, or if the shortening rate has increased during the late Quaternary.

List of Figures

Late Cenozoic structures of the eastern San Francisco Bay area, California, include both dextral faults of the San Andreas system, and map-scale folds and thrust faults. In a recent NEHRP study, Unruh and Sawyer (1997) identified and characterized several contractional structures in the Mt. Diablo-Livermore region as potential seismic sources. The largest structure is the Mt. Diablo anticline, which is approximately 25 km long, 22 km wide, and exhibits several kilometers of structural relief. Mt. Diablo anticline can be modeled as a southwest-vergent fault propagation fold above a blind, northeast-dipping thrust fault (Unruh and Sawyer, 1997). The dimensions of Mt. Diablo anticline are comparable to other Quaternary folds in western California such as the Coalinga anticline and the Santa Susana Mountains anticlinorium, which are underlain by blind thrust faults that have produced moderate magnitude earthquakes (i.e., the 1983 M6.5 Coalinga earthquake and the 1994 M6.7 Northridge earthquake, respectively).

Based on these initial studies, Unruh and Sawyer (1997) estimated that the blind Mt. Diablo thrust fault potentially is capable of producing a maximum $M_w 6^3/_4$ earthquake. They considered a range of values in horizontal shortening, fault dip and timing of deformation, and estimated that the minimum slip rate on the blind Mt. Diablo thrust fault is about 1.3 mm/yr (10 km total shortening; 30° fault dip; 9 Ma onset of shortening), and the maximum slip rate permitted by available data is about 7 mm/yr (17 km total shortening; 45° fault dip; 3.4 Ma onset of shortening). Using an intermediate value of about 4 mm/yr for the slip rate, the implied return time for moderate magnitude earthquakes that release about 1 to 2 m of accumulated slip on the thrust is about 250 to 500 yr (Unruh and Sawyer, 1997).

The goal of this current investigation is to perform new structural geologic studies and improve the preliminary characterization of the blind Mt. Diablo thrust fault of Unruh and Sawyer (1997). The work summarized in this report incorporates new information from on-going studies of late Neogene stratigraphy and paleogeography in this region, apatite fission-track analysis of the uplift of Mt. Diablo, and oil industry data released to the U.S. Geological Survey. These data are incorporated in a series of new balanced cross sections to refine interpretations of the subsurface structure and better constrain the long-term average slip rate of the Mt. Diablo thrust fault.

2.1 Late Cenozoic Tectonic Setting of Mt. Diablo Anticline

Mt. Diablo anticline is the largest fold in a belt of contractional structures that extends from the northern Diablo Range to the western Sacramento-San Joaquin Delta region (Figure 1). From south to north, these structures include the Williams and Verona thrust faults; the synformal Livermore basin; Tassajara anticline; Mt. Diablo anticline; Concord anticline; and the Los Medanos Hills anticlinorium. The folds exhibit a well-defined, right-stepping en echelon geometry, and are associated with an area of elevated, rugged and youthful topography that includes the 1,173 m peak of Mt. Diablo. For convenience, this group of structures is referred to as the Mt. Diablo fold-and-thrust belt. Neogene strata exposed on the northeast and southwest limbs of Mt. Diablo anticline contain several tephra ranging in age from 3.4 Ma to 11 Ma. The strata containing the tephra are fully involved in the folding, indicating that at least some if not most of the contractional deformation is late Neogene in age or younger.

Mt. Diablo anticline is a strongly asymmetric, doubly-plunging, southwest-vergent fold that forms the Mt. Diablo massif. The axis of the anticline is approximately 25 km long, and the maximum NE-SW width (i.e., wavelength) of the fold is approximately 22 km. The northeast limb of the anticline is a relatively simple northeast-dipping homocline that exposes Cretaceous and Tertiary strata (Figures 1 and 2). Bedding dips on the northeast limb range between 20° and 70°, with the majority of dips approximately 45°. In contrast, the southwest limb of the fold is represented by vertical to overturned Cretaceous through late Neogene strata that underlie a series of prominent west-northwest-trending strike ridges. In the region of greatest topographic and structural relief, Mt. Diablo anticline is cored by rocks of the Franciscan assemblage and the Coast Range ophiolite (Figure 1).

Unruh and Sawyer (1995) proposed that crustal shortening in the Mt. Diablo fold-and-thrust belt is associated with a restraining left-stepover or transfer of dextral slip from the Greenville fault southeast of Mt. Diablo to the Concord fault northwest of Mt. Diablo (Figure 1). In this model, most of the dextral slip is transferred from the Greenville fault to the Concord fault across the Mt. Diablo anticline, but west-northwest-trending folds in the Tassajara Hills and Livermore Valley south of Mt. Diablo, as well as the Los Medanos Hills anticlinorium and folds in the western Delta region to the north, indicate that dextral shear probably is distributed across a broad north-south zone between the Greenville and Concord faults that is approximately centered on Mt. Diablo anticline. This model is consistent with the oblique trends of the contractional structures relative to the major strike-slip faults, the right-stepping, en echelon geometry of the contractional structures, and the observation that the maximum topographic relief in the belt occurs at Mt. Diablo anticline.

2.2 Stratigraphy

Three major tectono-stratigraphic units representing elements of the ancestral western California convergent margin are exposed on the limbs and across the axis of Mt. Diablo anticline (Figure 1). The structurally lowest unit is the Franciscan complex, which consists of metamorphosed basalt, chert, shale and sandstone that accumulated in an accretionary wedge. Williams (1983) reported the occurrence of jadeite and pumpellyite in basalt blocks within the Franciscan complex at Mt. Diablo, and individual knockers of blueschist rocks also are present (R. Coleman, personal communication, 1999), indicating that at least some of the Franciscan rocks were subjected to high pressure, low temperature metamorphism at great depth in a subduction zone. Based on analysis of apatite fission-track data from Mt. Diablo, uplift of the blueschist-grade Franciscan rocks
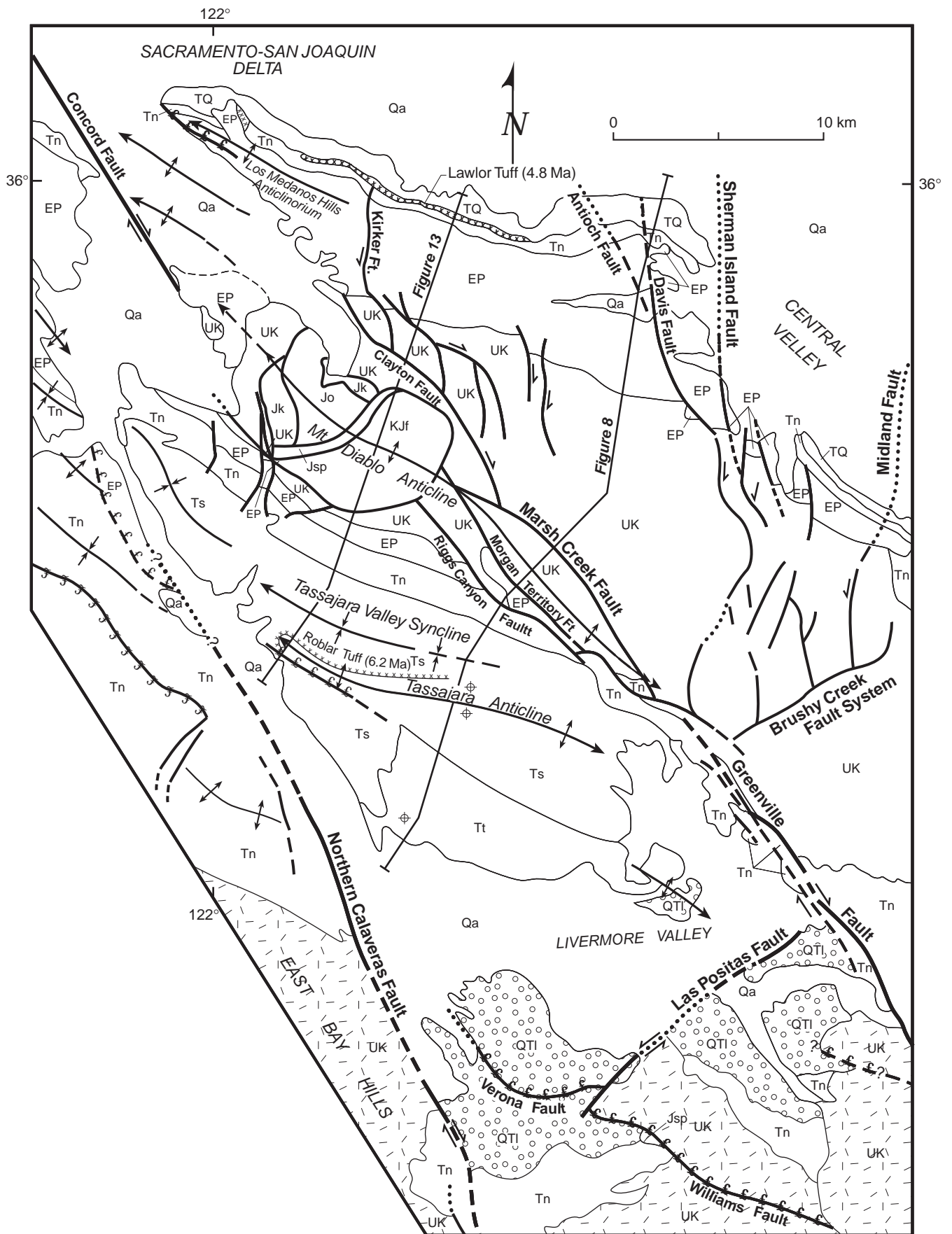
Figure 1. Geologic map of Mt. Diablo and environs (modified from Wagner et al., 1990; Krug et al., 1992; Crane, 1995; and Andersen et al., 1995).

EXPLANATION

| Qa | Upper Quaternary alluvium

LIVERMORE BASIN DEPOSITS

| QTl | Livermore Gravels (Quaternary)

| Tt | Tassajara Formation (Pliocene-Quaternary) | TQ | Pliocene-Pleistocene strata, undivided

| Ts | Sycamore Formation (Miocene-Pliocene)   xxxx Lawlor Tuff (4.8 Ma)

xxxx Roblar Tuff (6.2 Ma)

| Tn | Neogene Strata, undivided

| EP | Paleocene-Eocene marine fore-arc strata

| UK | Upper Cretaceous Great Valley Group
——Fault——

| Jk | Upper Jurassic Great Valley Group ("Knoxville Formation")
——Fault——

| Jo | Upper Jurassic Coast Range Ophiolite | Jsp | Coast Range Ophiolite serpentinite
——Fault——

| KJf | Franciscan Complex (Upper Jurassic)

⇉—••? Strike-slip fault (dashed where approximate, dotted where inferred, queried where uncertain)

£ £ £ Thrust fault (teeth on hanging wall)

—— – – Fault; dashed where approximately located, dotted where covered

→ Fault showing relative stratigraphic offset

↔ Plunging anticline

↕ Plunging syncline

⊕ Exploration well

⊢——⊣ Cross-section line
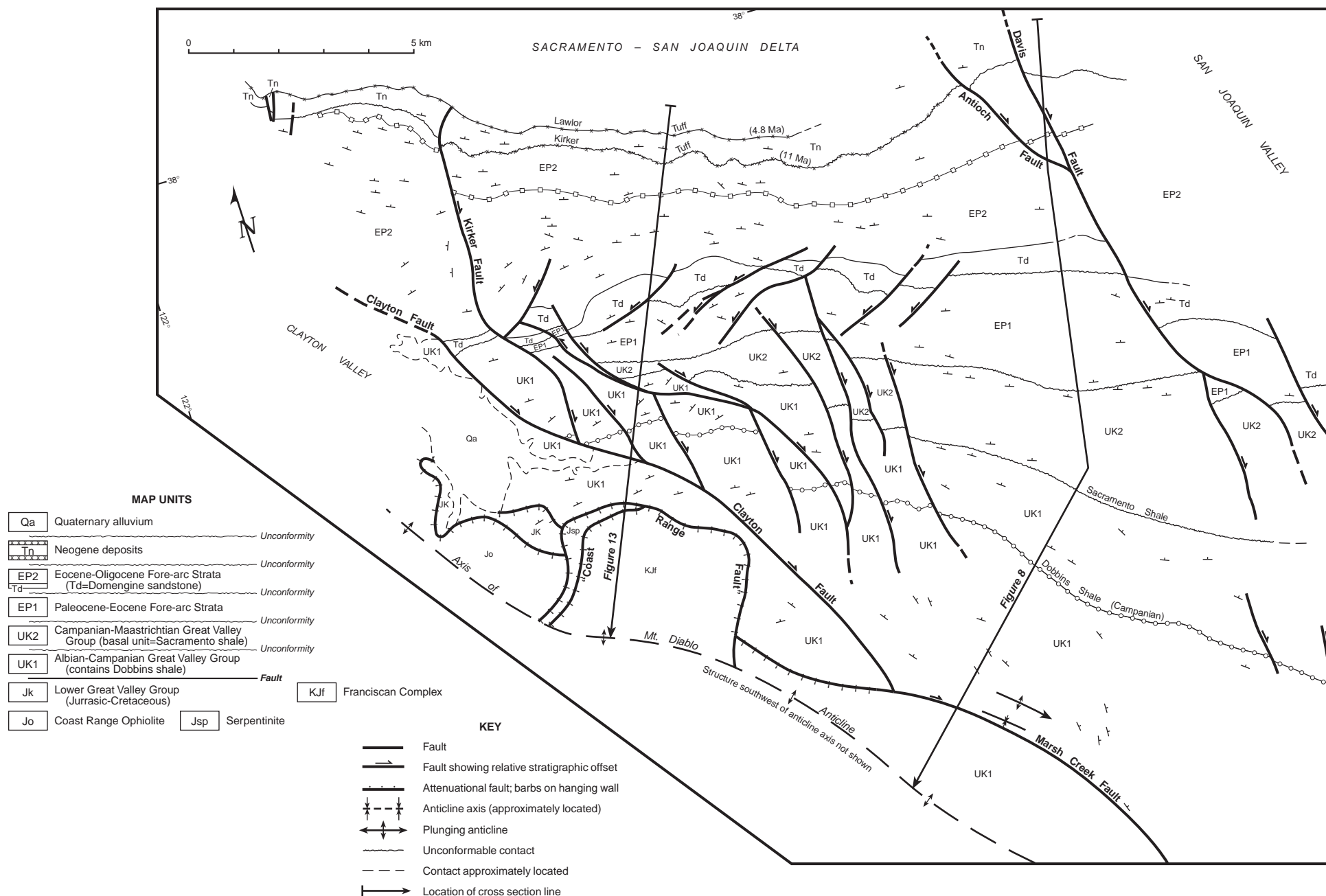
Figure 2. Geologic map of the northeast limb of the Mt. Diablo anticline (modified from Graymer et al. 1994).
Map is oriented so that the base of the Neogene section (i.e., the 11 Ma Kirker tuff) is horizontal.

through the apatite annealing temperature occurred in early Tertiary time (about 60 Ma; Burke et al., 1997).

On the northwest side of Mt. Diablo, the Franciscan complex is structurally overlain by remnants of the Coast Range ophiolite (Figures 1 and 2), which represents the basement of the ancestral fore-arc region. From bottom to top, major units of the ophiolite include: blocks of harzburgite and pyroxenite in a 300-m-wide band of serpentinite melange, a diabase screen, leucocratic dikelets, sheeted diabase dikes, and extrusive basalts (Williams, 1983). Gabbro and peridotite found the lower parts of some ophiolite complexes are missing from the pseudostratigraphic section at Mt. Diablo (Williams, 1983).

Structurally overlying both the Franciscan complex and ophiolitic rocks are Mesozoic and early Tertiary fore-arc basin deposits (Moxon, 1990). The fore-arc deposits in turn are unconformably overlain by late Neogene to Quaternary marine and terrestrial deposits that span the transition from convergent margin tectonics to transpressional motion along the Pacific-North American plate boundary (Nilsen and Clark, 1989; Isaacson and Andersen, 1992). Detailed descriptions of Mesozoic to late Cenozoic stratigraphic units in the Mt. Diablo region are presented in Fox (1983), Graham et al. (1983), Nilsen and Clarke (1989), Moxon (1990), Isaacson and Andersen (1992), Krug et al. (1992), Graymer et al. (1994), Crane (1995), and Andersen et al. (1995). Of particular importance for this study are the upper Cretaceous through Eocene marine forearc deposits that comprise the majority of the exposed section on the northeast flank of Mt. Diablo anticline (Figures 1 and 2). Moxon (1990) grouped these strata into several discrete stratigraphic packages bounded by unconformities:

Package UK-1. As defined by Moxon (1990), this package consists of Albian to Campanian age sediments of the Great Valley Group. Regionally, package UK-1 is a transgressive sequence that records rapid subsidence of the ancestral forearc region to lower middle to lower bathyal depths (Moxon, 1990). At Mt. Diablo, however, the depositional base of package UK-1 is not exposed; instead, Albian strata of UK-1 rest structurally on underlying Upper Cretaceous Great Valley Group strata (undifferentiated), upper Jurassic Great Valley Group rocks (commonly referred to as "Knoxville Formation"), tectonic slivers of Coast Range ophiolite and the Franciscan complex (Figure 2). The major structure at the base of UK-1 is the Marsh Creek-Clayton fault system, which strikes northwest, dips northeast, and lies northeast of the axis of Mt. Diablo anticline (Figure 2). The Campanian Dobbins shale is present within UK-1 (Figure 2) and forms a widespread stratigraphic marker throughout large areas of the relict fore-arc basin in California's Central Valley.

Package UK-2. This package includes Campanian-Maastrichtian Great Valley Group strata. Regionally, package UK-2 is a regressive sequence that is associated with uplift or shoaling of the ancestral forearc basin in the Mt. Diablo area to middle to upper middle bathyal depths (Moxon, 1990). The base of UK-2 is marked by the Sacramento shale, another widespread stratigraphic marker in the subsurface of the Central Valley east of Mt. Diablo.

Package EP-1. This unit includes Paleocene-Eocene marine strata that rest unconformably on rocks of UK-1 and UK-2 in the Mt. Diablo area. Package EP-2 consists of two separate sequences, each of which is marked by deposition of a transgressive sand followed by erosion and filling of a submarine gorge (Moxon, 1990). Based on analysis of microfossils, Moxon (1990) interpreted that package EP-1 was deposited in middle to upper middle bathyal water depths.

Package EP-2. This unit consists of Eocene-Oligocene marine strata. The base of this package is marked by the transgressive Domengine sandstone (Moxon, 1990; Figure 2). In the Mt. Diablo area, the Domengine sandstone unconformably overlies rocks of packages EP-1, UK-2 and UK-1,

indicating the presence of substantial structural relief on the older units by early EP-2 time. In general, the Domengine sandstone rests on progressively older strata moving from east to west (Moxon, 1990), suggesting that eastward tilting of the older strata occurred during EP-1 time or earlier. Based on analysis of microfossils, Moxon (1990) inferred that the ancestral Mt. Diablo area rapidly subsided to lower middle bathyal depths during deposition of package EP-2 in lower Eocene time.

Late Miocene shallow marine and continental strata unconformably overlie rocks of package EP-2. The Neroly Formation, a volcaniclastic sandstone derived from erosion of Miocene volcanic rocks in the Sierra Nevada east of Mt. Diablo, is at or near the base of the Neogene section on both limbs of Mt. Diablo anticline (Figures 1 and 2). The Neroly Formation was deposited in shallow marine to nearshore environments (Andersen et al., 1995), and thus indicates shoaling of the fore-arc region relative to EP-2 time. Based on fossil fauna and stratigraphic relationships, the Neroly Formation was deposited between about 9 and 11 Ma (Andersen et al., 1995).

The Neroly Formation is conformably overlain on the southwest side of Mt. Diablo by the Sycamore Formation, which consists of approximately 3,000 m of late Miocene to Quaternary continental strata eroded from local topographic highs and deposited in the ancestral Livermore basin (Isaacson and Andersen, 1992). The Sycamore Formation contains the 6.2 Ma Roblar Tuff and 4.8 Ma Lawlor Tuff, both of which are involved in the folding of Mt. Diablo and Tassajara anticlines (Sarna-Wojciki, 1976; also A. Sarna-Wojciki, personal communication, 1999). The Sycamore Formation locally is overlain by the Plio-Pleistocene Tassajara Formation and the Pleistocene Livermore gravels (Figure 1; Andersen et al., 1995). These deposits also are involved in late Cenozoic contractional deformation of the Mt. Diablo fold and thrust belt.

As noted by Moxon (1990), the Cretaceous-Neogene stratigraphic sections are markedly different in character and thickness on the opposite flanks of the Mt. Diablo anticline. The combined thickness of Cretaceous and early Tertiary strata measured from outcrop exposures on the northeast limb of the fold is approximately 5 km, and the youngest Tertiary rocks underlying the late Miocene Neroly Formation are Oligocene in age. The Neroly Formation and overlying Plio-Pleistocene strata are several hundred meters thick at most. In contrast, the combined thickness of Cretaceous and early Tertiary strata in outcrop on the southwest flank of Mt. Diablo is 1.0 km or less, and the youngest Tertiary rocks beneath the basal Neogene strata are Eocene in age (i.e., basal EP-2 strata). The Neogene section is at least 3 km thick on the southwest limb of Mt. Diablo anticline (Andersen et al., 1995), and the full thickness beneath Livermore Valley probably is about 5 km, based on seismic refraction studies (Meltzer, 1988). The significance of the differences in the stratigraphic sections on opposite limbs of Mt. Diablo anticline is discussed in detail below.

2.3 Structural Geology of Mt. Diablo Anticline

2.3.1 Cretaceous-Tertiary Structure

Previous workers (e.g., Krug et al., 1992; Crane, 1995) recognized a series of faults on the northeastern flank of Mt. Diablo that primarily displace Eocene and older strata. These structures include the Kirker fault and the Clayton-Marsh Creek fault system (Figures 1 and 2). As noted by Crane (1995), stratigraphic and structural relationships visible in outcrops on the northeastern flank of Mt. Diablo are consistent with early Tertiary syn-sedimentary normal displacement on these faults. When viewed down dip, the homoclinally northeast-tilted section on the northern side of the mountain provides an approximately cross-sectional view of the upper 6 to 7 km of the crust (Crane, 1995). To facilitate viewing the structure in this manner, the geologic map of the northeast limb of Mt. Diablo anticline (Graymer et al., 1994) is oriented in Figure 3 so that the base of the Neogene section is subhorizontal, and the vertical scale has been compressed digitally so that the
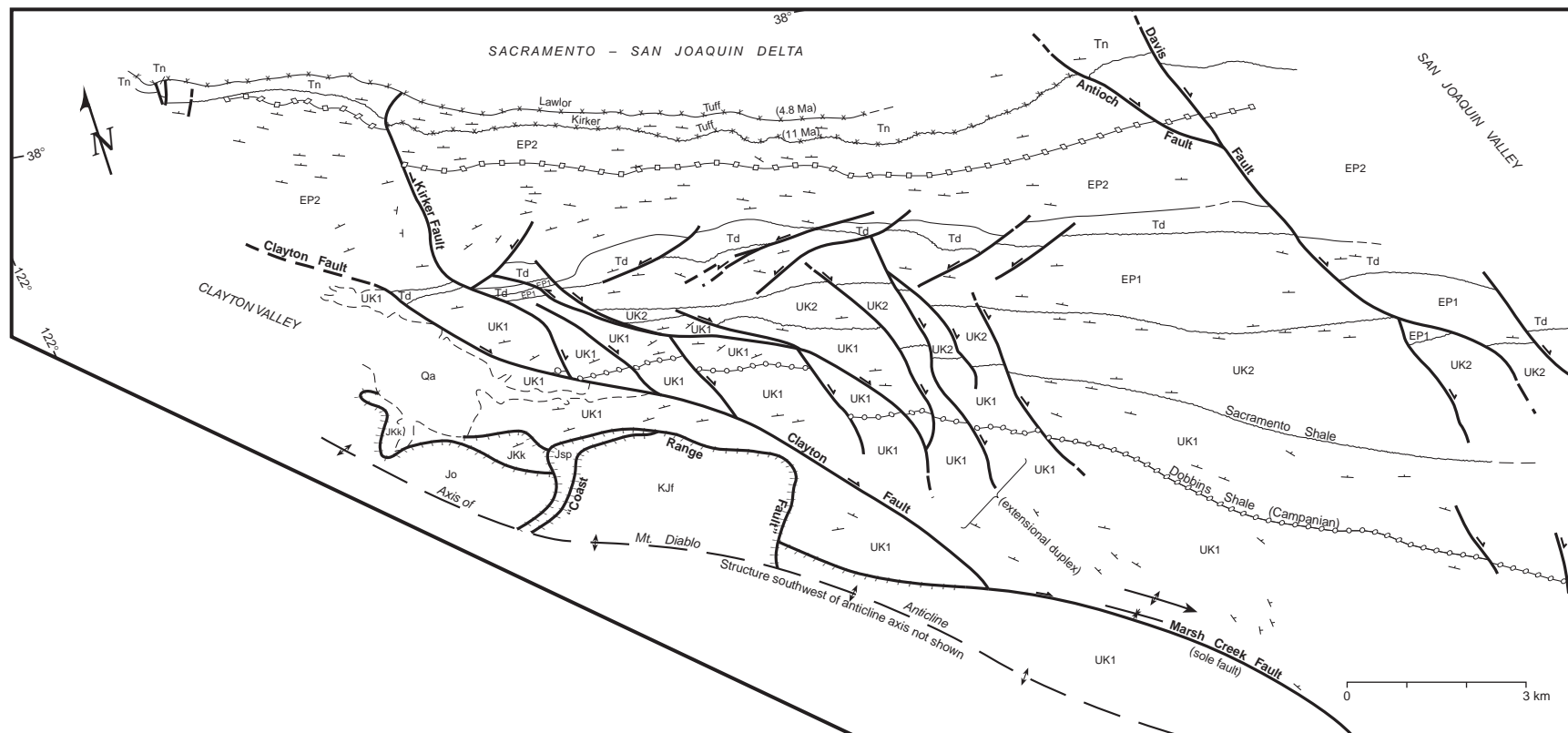
Figure 3. Approximate down-dip view of structural and stratigraphic relations on the northeast limb of Mt. Diablo anticline. Figure was prepared by compressing the vertical dimension of the geologic map in Figure 3 so that the apparent thickness of stratigraphic units as viewed down dip is similar to the true thickness measured normal to bedding dip. The resulting figure provides an approximate cross-sectional view of the upper 3-7 km of the crust.

thicknesses of the stratigraphic units in map view are approximately equal to their true thicknesses relative to the horizontal scale. The resulting map (Figure 3) approximates the appearance of the map units when viewed down dip on a geologic map.

In this down-structure view (Figure 3), the Kirker fault cuts downsection through the Eocene strata at a high angle to bedding and terminates against the Clayton fault which is at a relatively low angle to bedding strike. The exposed section of Cretaceous and Eocene strata is thicker on the east side of the Kirker and Clayton faults than on the west side, and in particular the combined Paleogene section (packages EP-1 and EP-2) thickens significantly to the southeast of the Kirker fault. The down-structure view in Figure 3 also shows that numerous short faults southeast of the Kirker fault cut downsection and terminate against the Clayton fault. Displacement of the Dobbins shale marker across these faults shows a consist sense of southeast-side-down displacement and rotation of bedding into the plane of the Clayton fault, as well as thickening of the UK-1 section southeast of the fault.

The down-structure view in Figure 3 further reveals that the Clayton fault is linked to a fault or system of faults that juxtapose UK-1 strata, Upper Jurassic Great Valley Group rocks (i.e., "Knoxville Formation"), serpentinite and volcanic rocks of the Coast Range ophiolite, and the Franciscan complex. Specifically, the Clayton fault roots into the Marsh Creek fault, which strikes at a low angle to bedding in the overlying UK-1 section. The Marsh Creek fault in turn is linked to a fault that extends northwest and terminates against the structural contact between the blueschist-bearing Franciscan complex and unmetamorphosed UK-1 strata. The difference in metamorphic grade across this contact represents omission of many kilometers of crustal section. Fault-bounded remnants of the attenuated crustal section between the Franciscan complex and the Great Valley Group are exposed on the northwest-plunging nose of the Mt. Diablo anticline, structurally below the Clayton fault (Figure 3). These rocks include the ophiolitic basement and lower Great Valley Group strata.

Following Crane (1995), the stratigraphic and structural relations in Figures 2 and 3 here are interpreted as evidence for crustal extension and syn-tectonic deposition in an actively subsiding Cretaceous-Tertiary graben. The sole fault or basal detachment for the graben is the Clayton-Marsh Creek fault system (Figure 2). Fault-bounded blocks above the Clayton-Marsh Creek fault exhibit rotation of bedding dips into the fault plane consistent with domino-style normal faulting. In particular, several fault blocks structurally overlying the Clayton fault are bounded above by a normal fault or faults that are at a low angle to bedding, and which accommodated displacement and thickening of UK-2 and EP-1 strata (Figure 3). Collectively, the domino-style fault blocks, the Clayton fault, and the low-angle faults above the blocks comprise an extensional duplex (Crane, 1995).

Based on offsets of sequence-bounding unconformities, bedding contacts and marker horizons on the northeast limb of Mt. Diablo, growth faulting occurred during deposition of the UK and EP sequences, i.e. at least from Albian to Eocene time. The stratigraphic and structural relations on Figure 2 also indicate that some normal displacement of the 11 Ma Kirkertuff at base of the late Miocene Neroly Formation probably occurred across the Kirker fault and Antioch-Davis fault. Mapping by Graymer et al. (1994) indicates that Pliocene strata containing the 4.8 Ma Lawlor Tuff are not displaced by the Kirker or Antioch-Davis faults. If these stratigraphic relations are correctly interpreted, then movement on the normal faults either persisted into late Miocene time at a low rate of activity, or there was modest extensional reactivation of the faults in late Neogene time. Normal slip on the faults apparently ceased by 4.8 Ma.

Previous workers (Krug et al., 1992; MacKevett, 1992) have recognized that the faults on the northeast flank of Mt. Diablo anticline continue northward in the subsurface of the Sacramento-San

Joaquin delta region (Figure 4). The Kirker fault joins the Kirby Hills fault and comprises the western margin of an approximately north-trending graben or structural trough (Figure 4). The eastern structural boundary of the graben is the Midland fault, which has been traced in the subsurface south to the outcrop belt on the southeastern flank of Mt. Diablo and terminates against the Brushy Creek fault system (Krug et al., 1992; Figures 1 and 4). The Brushy Creek system in turn terminates against or roots into the Clayton-Marsh Creek fault system, similar to the Kirker fault. The 3-D relationship between the fault traces in plan view in the delta region and the down-structure view on Mt. Diablo can be observed by noting that the synformal hinge at the base of the northeast limb of Mt. Diablo anticline is analogous to a "fold line", used by structural geologists to construct vertical profiles of faults and folds from map and plan data (Figure 4).

The attenuation of crust represented by juxtaposition of the blueschist-bearing Franciscan rocks against Upper Cretaceous Great Valley Group strata across Marsh Creek-Clayton fault system is consistent with relationships attributed to the "Coast Range fault" by Jayko et al. (1987). We thus conclude that the Clayton-Marsh Creek fault system, as well as the ancillary structures that disrupt the Coast Range ophiolite and lower Great Valley Group rocks (Figure 4), are the local expression of the "Coast Range fault" at Mt. Diablo. The structural relations in Figure 4 indicate that the upper crustal graben bounded by the Kirker-Kirby Hills and Midland-Brushy Creek faults is rooted in the low-angle Clayton-Marsh Creek fault, which in turn is linked to the Coast Range fault system. The period of major subsidence within the graben (late Cretaceous-early Tertiary) is coeval with rock uplift and exhumation of the Franciscan complex indicated by AFT cooling ages (Burke et al., 1998). The map relations in Figure 4 thus depict a kinematic link between upper crustal extension in the fore-arc region and attenuation of the middle crust during late Cretaceous-early Tertiary plate convergence and subduction.

2.3.2 Neogene Stratigraphy and Structure

The Neogene section that rests unconformably on unit EP-2 thickens radically from northeast to southwest across the axis of Mt. Diablo anticline. On the northeast limb, the Neogene section consists of about 200 m to 400 m of late Miocene and Pliocene shallow marine and continental fluvial deposits, and primarily is represented by the Neroly Formation, which is underlain by the 11 Ma Kirker tuff and overlain by the 4.8 Ma Lawlor tuff (Figure 2). In contrast, the Neroly Formation on the southwest limb of the anticline is part of a much thicker late Miocene section, and it is overlain by a minimum of 3000 m of continental fluvial deposits assigned by Issacson and Andersen (1992) and Andersen et al. (1995) to the late Neogene Sycamore Formation (Figure 5). The Sycamore Formation contains several tephra ranging in age from 3.3 to 6.2 Ma (Graymer et al., 1994; Isaccson and Andersen, 1992; J. Walker, personal communication, 1999). Despite the very different thicknesses of the late Neogene sections on opposite limbs of Mt. Diablo anticline, temporal equivalence between them is established by the tephra.

Data from exploratory wells drilled in the Tassajara anticline southwest of Mt. Diablo provide evidence for a minimum thickness of 4 km of late Neogene and younger strata on the southwest limb of Mt. Diablo anticline (Figure 5). The Hans Nielsen No. 1 well was drilled on the axis of the Tassajara anticline to a total depth of 4,033 m (13,231 ft). An annotated e-log for this well provided by Chevron shows the "top Miocene" picked at a depth of 2097 m (6,880 ft), apparently based on a change in lithology. Eocene rocks were encountered at a depth of about 3,720 m (12,200 ft), and identified as Nortonville Formation based on lithology and fossil fauna. The Nortonville Formation crops out on the northeast side of Mt. Diablo and directly overlies the Domengine Formation; thus, Eocene strata encountered below the Miocene section in the Hans Nielsen well are part of the EP-2 package (Figure 5). The unconformable contact between EP-2 and the Miocene strata exposed on the southwest limb of Mt. Diablo anticline can be plausibly projected westward in the subsurface through the axis of the Sycamore Valley syncline to the top
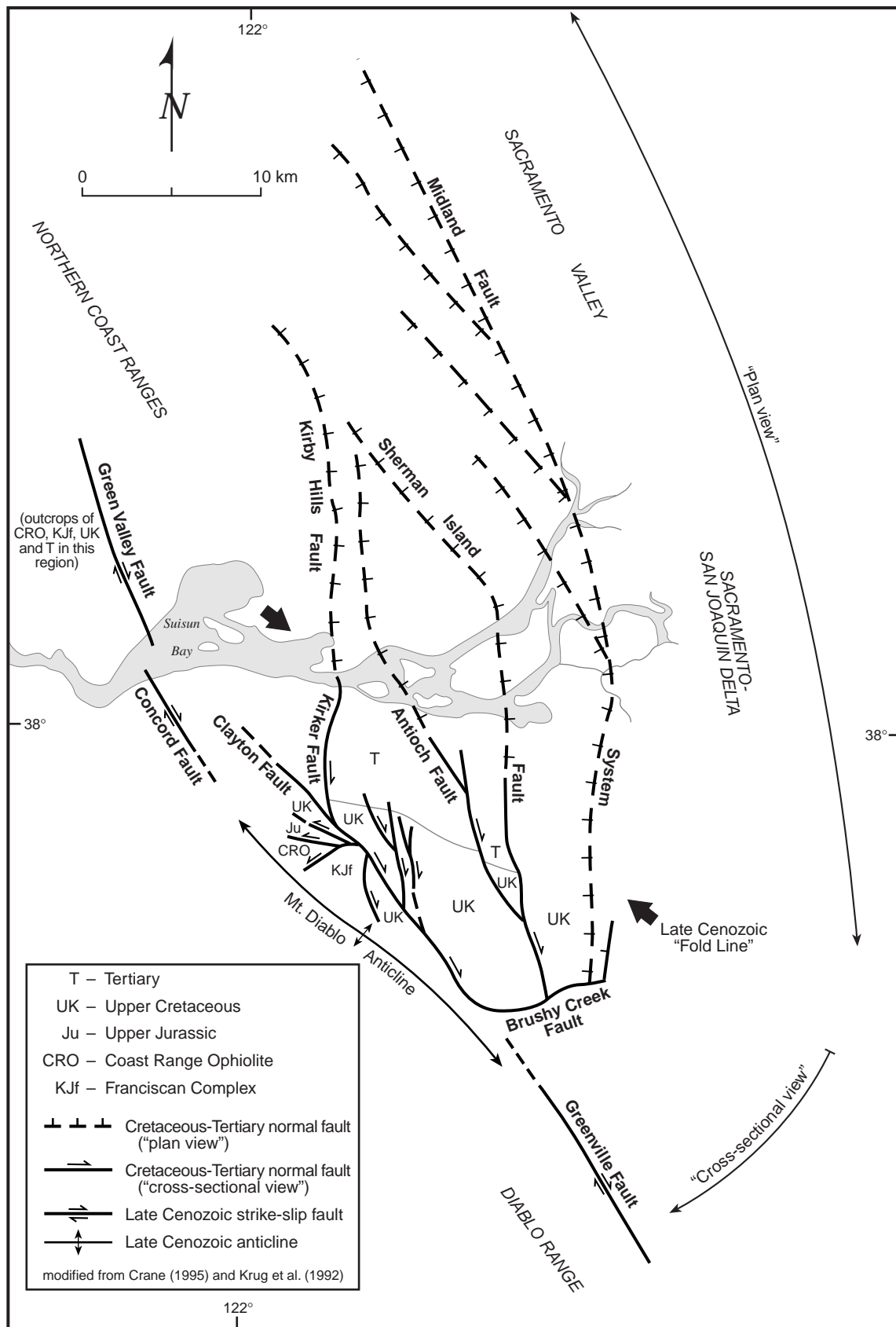
Figure 4. Northward, subsurface projection of major faults exposed on the northeast limb of Mt. Diablo anticline. The faults define an approximately north-south-trending graben that underlies that Sacramento-San Joaquin delta and the southern Sacramento Valley. Uplift and folding of Mt. Diablo anticline has exposed a cross-sectional view of the graben system on the northeast limb of the fold. The synformal hinge at the base of the anticline forelimb is equivalent to a "fold line" (see text for discussion).
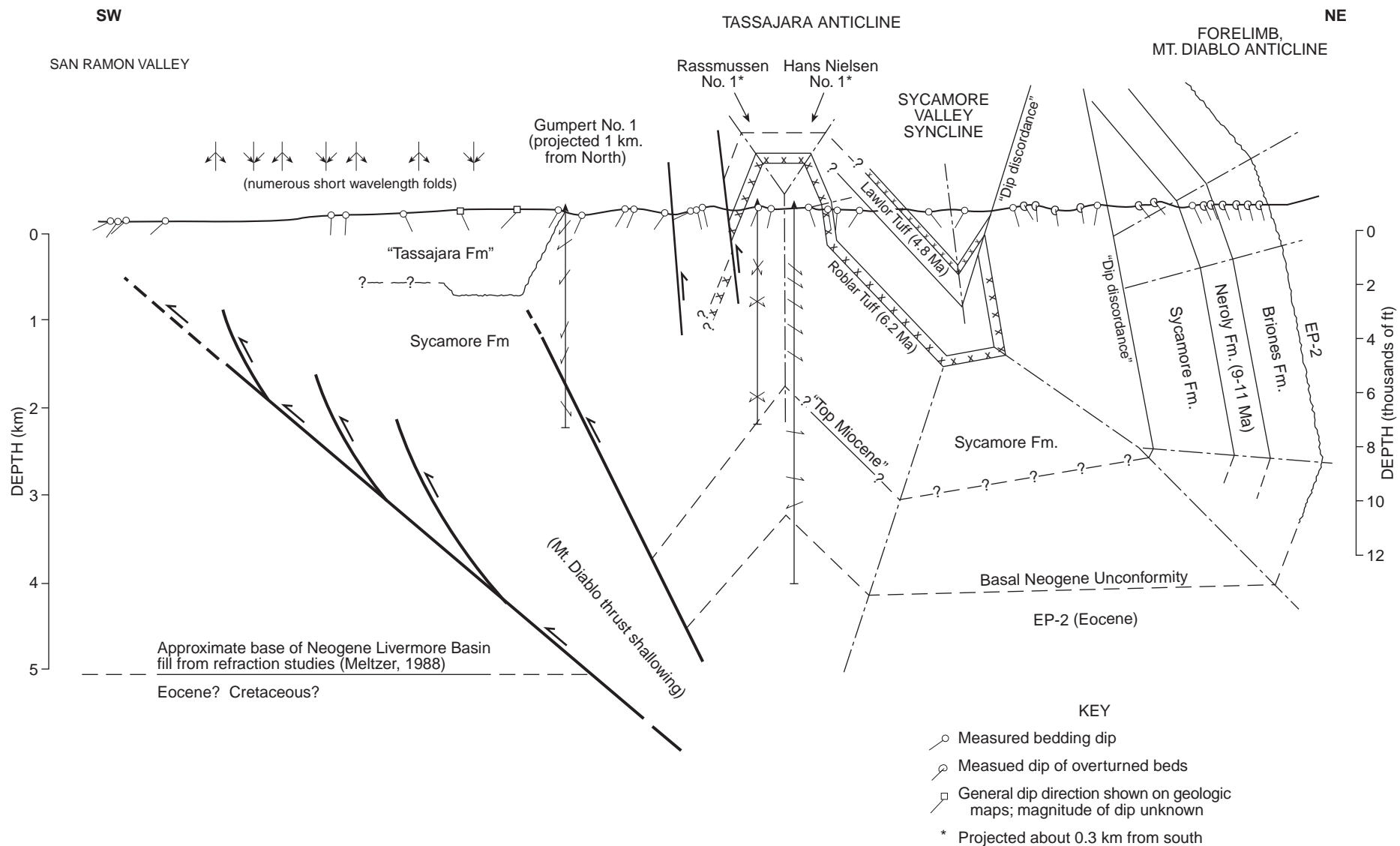
Figure 5. Shallow cross-section drawn through three deep wells drilled in the Tassajara anticline (this section is located slightly south of the regional cross-section in Figure 8). Section illustrates how Eocene strata (EP-2) exposed on the forelimb of the Mt. Diablo anticline can be traced through the axis of the Sycamore Valley syncline and tied to coeval rocks encountered in the Hans Nielsen no. 1 well. Cross-section highlights abrupt "dip discordances" in the late Neogene Sycamore Formation that may be angular unconformities. Cross-section also interprets the "Tassajara Formation" (see map, Figure 1) to be a shallow unit that primarily overlies the Sycamore Formation west of Tassajara anticline.

of the Eocene in the Hans Nielsen well (Figure 5). The thickness of the late Neogene section measured perpendicular to bedding dip on the northeast limb of Tassajara anticline is about 4 km. The cross section in Figure 4 implies that the total thickness of the Neogene section above EP-2 may be greater than 4 km in the axis of the Sycamore Valley syncline. This estimate is uncertain, however, because possible angular unconformities in the Sycamore Formation (discussed below) make it difficult to confidently project surface bedding dips to depth and constrain the subsurface geometry of the Neogene-Eocene contact.

The Sycamore Formation was deposited in the ancestral Livermore basin, a late Neogene depocenter located along the southwestern flank of the present Mt. Diablo massif (Nilsen and Clarke, 1989; Isaccson and Andersen, 1992; Andersen et al., 1995). Drill hole and seismic refraction data suggest that the thickness of the Livermore basin fill to the southwest of Mt. Diablo is about 5,000 m (Meltzer, 1988). The exact mechanism by which the basin formed is not known. Nilsen and Clark (1989) described ancestral Livermore basin as a remnant of a complex fore-arc basin associated with early to middle Neogene subduction. Stratigraphic relationships on the southwest limb of Mt. Diablo anticline indicate that major subsidence of the basin began after 11 Ma, however, roughly coincident with the passage of the Mendocino triple junction and transition of the region from a fore-arc setting to a transcurrent or transpressional setting (Buising and Walker, 1995; Atwater and Stock, 1999). Deposition of the 3000+ m thick Sycamore Formation occurred between about 8.5 Ma and 3.5 Ma (Andersen et al. 1995), well after the passage of the triple junction. There is no early to middle Neogene section exposed at Mt. Diablo marking the presence of a Neogene basin that predated the Livermore basin, although older Neogene strata of the Contra Costa basin are exposed northwest of Mt. Diablo in the East Bay hills (Graham et al., 1984). The modern structural boundaries of Livermore basin are Mt. Diablo to the northeast and the Calaveras fault to the west; these structures offset and deform the basin fill, and appear to postdate major late Neogene subsidence of the basin (Nilsen and Clark, 1989; Andersen et al., 1995). Thus, the origin of Livermore basin and the mechanism for producing 3 to 5 km of subsidence between about 11 Ma and 4 Ma in a transcurrent to transpressional setting are not well understood.

Some insight into the style of basin subsidence may be inferred from patterns of bedding dips in the late Neogene section on the southwest side of Mt. Diablo (Figures 5 and 6). Moving southwest from the axis of the fold, UK-1, EP-2, late Miocene and lower Sycamore Formation strata are overturned and dip 40° to 70° to the northeast. There is an abrupt change in dip several hundred meters southwest of the basal Sycamore strata, where a stratigraphically higher panel of vertical beds is juxtaposed against a stratigraphically lower panel of overturned beds. Another abrupt change in bedding dip occurs just northeast of the Sycamore Valley syncline axis, such that the youngest Sycamore strata in the syncline dip about 60° to 80° southwest and are juxtaposed against the panel of vertical to overturned beds to the northeast (Figure 6). If it is assumed that the upper Sycamore beds in the syncline axis were subhorizontal when deposited, then the relationships described above and shown in Figures 5 and 6 depict progressive steepening of dip downsection in the late Neogene strata and underlying EP-2 and UK-1 packages.

Although several explanations of these relations are possible (see Crane, 1995, for an alternative interpretation), downward steepening of bedding dips could have been produced by progressive down-to-the-southwest tilting in Livermore basin during deposition of the Neroly and Sycamore Formations. In this interpretation, southwest-down tilting along the basin margin accompanied subsidence of the basin, thus accounting for the radical increase in the thickness of the late Neogene section across the axis of Mt. Diablo anticline. The abrupt changes in bedding dip noted on Figures 5 and 6 (i.e., "dip discordance") may be angular unconformities within the Neogene section related to tilting during active subsidence along the northeastern margin of ancestral Livermore basin.
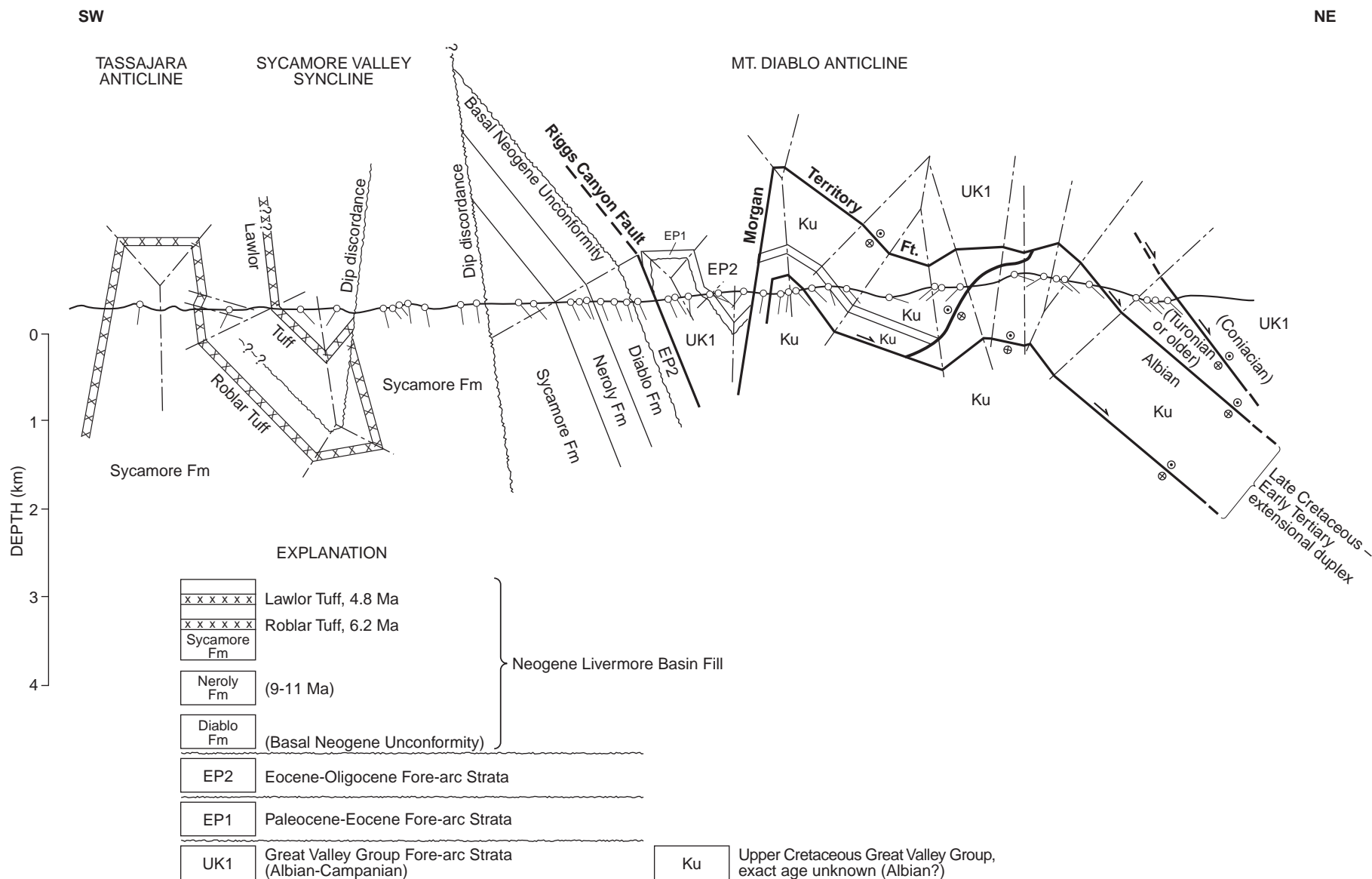
Figure 6. Shallow cross-section showing detail along the line of the regional cross-section in Figure 8. The section presents an interpretation showing that faults at a low angle to bedding (e.g., the Morgan Territory fault and Marsh Creek fault) are part of the basal detachment system for the north-trending graben shown in Figure 5; the detachment system is folded about the axis of the Mt. Diablo anticline. Stratigraphic relations among Cretaceous rocks northeast of the anticline axis are consistent with omission of section by these faults.

A series of restorable cross sections was prepared to assess the geometry of late Cretaceous-early Tertiary extensional structures at Mt. Diablo prior to late Cenozoic uplift and folding. In the following sections, the approach used to prepare the cross sections is described first, followed by a discussion of the structure of Mt. Diablo prior to Neogene subsidence of Livermore basin.

3.1 Kinematic Model for Late Cenozoic Folding

Both the Mt. Diablo and Tassajara anticlines are asymmetric, southwest-vergent folds. Using other, well-studied asymmetric folds as analogues (see examples in Woodward et al., 1989), Unruh and Sawyer (1997) inferred that the Mt. Diablo and Tassajara anticlines are fault-propagation folds developed above a blind, northeast-dipping thrust fault (or faults).

This interpretation is consistent with features visible in proprietary seismic reflection profiles from the northern Livermore Valley and southwestern Tassajara Hills. A time section acquired by Chevron (Figure 7) generally shows subhorizontal, layered, coherent reflectors extending to a minimum depth of about 4.0 seconds twt (two-way travel time) beneath Livermore Valley. The layered reflectors dip southwest along the southern margin of the Tassajara Hills (Figure 6), consistent with southwest dips of Sycamore Formation and younger strata mapped at the surface (Graymer et al., 1994; Crane, 1995). The synformal hinge at the base of the Tassajara anticline forelimb is visible beneath the northern Livermore Valley in the time section (Figure 7). At the northeast end of the seismic line, southwest-dipping layered reflectors of the Tassajara anticline are truncated at a depth of about 3.0 seconds twt, and juxtaposed against subhorizontal to moderately northeast-dipping reflectors below about 3.0 to 3.5 sec depth twt. The subhorizontal reflectors continue to the northeast end of the seismic line, where they underlie the southwest-dipping Sycamore strata mapped at the surface.

The juxtaposition of the southwest-dipping reflectors against the subhorizontal reflectors beneath the Tassajara anticline forelimb is interpreted to mark the position of a blind, northeast-dipping thrust fault (Figure 7), consistent with the inference that Tassajara anticline is a southwest-vergent fault-propagation fold (Unruh and Sawyer, 1997). Although the seismic line (Figure 7) does not continue northeast beyond the forelimb of Tassajara anticline, the blind thrust fault probably dips beneath the Tassajara anticline, and extends downdip to a depth of about 15 to 17 km, which is at or near the base of seismicity in this region (Oppenheimer and Macgregor-Scott, 1992). In this interpretation, both the Tassajara and Mt. Diablo anticlines are fault-propagation folds developed above a single northeast-dipping thrust fault (Figure 8). Mt. Diablo anticline probably began growing first, at which time the tip of the blind thrust fault was located several km down-dip beneath the forelimb of Mt. Diablo anticline. Subsequently, the fault tip propagated upward and Tassajara anticline began to form. Tassajara anticline currently is the locus of active fault-propagation folding associated with slip on the fault. Mt. Diablo anticline is part of the inactive hangingwall block, and is passively translated upward along the fault without significant new folding during individual slip events.

3.2 Restoration Approach

The kinematic model described above provided a basis for sequentially restoring deformation associated with growth of the Tassajara and Mt. Diablo anticlines. Folding associated with the Tassajara anticline was restored first. Using a pin line in the axis of the Sycamore Valley syncline as a reference for bed length comparisons, various models for the position and dip of the Mt.

SW

NE

LIVERMORE VALLEY

SOUTHWEST LIMB, TASSAJARA ANTICLINE

DEPTH IN SECONDS (two-way time)

0

1.0

2.0

3.0

4.0

Mt. Diablo Thrust fault.

0

1

2

3

4

DISTANCE (kilometers)

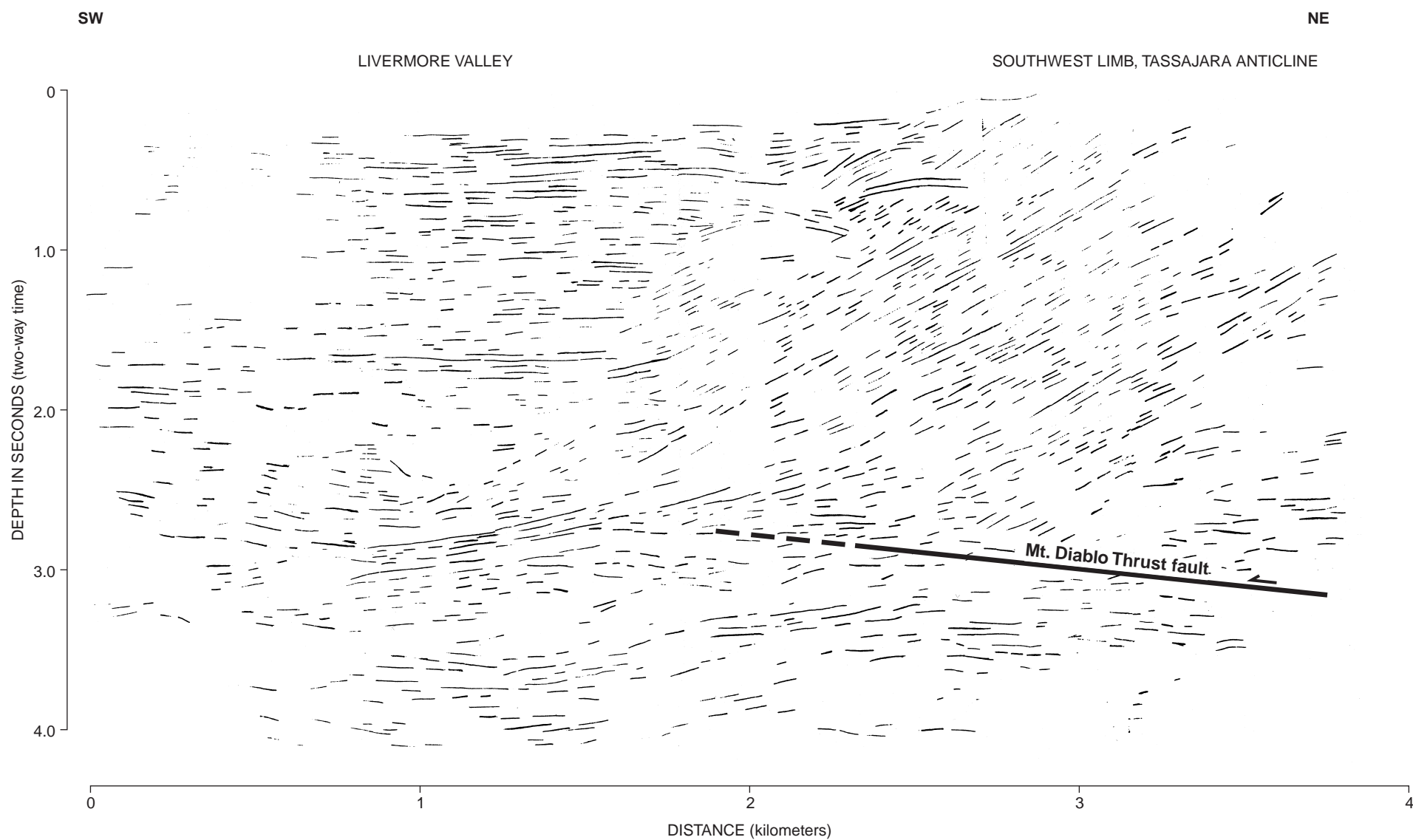Figure 7. Line drawning of SW-NE seismic time section acquired in northern Livermore Valley at the southeast end of the Tassajara Hills. The dip discordance of seismic markers beneath the forelimb of the Tassjara anticline is interpreted to mark the tip of a blind, northeast-dipping thrust fault.
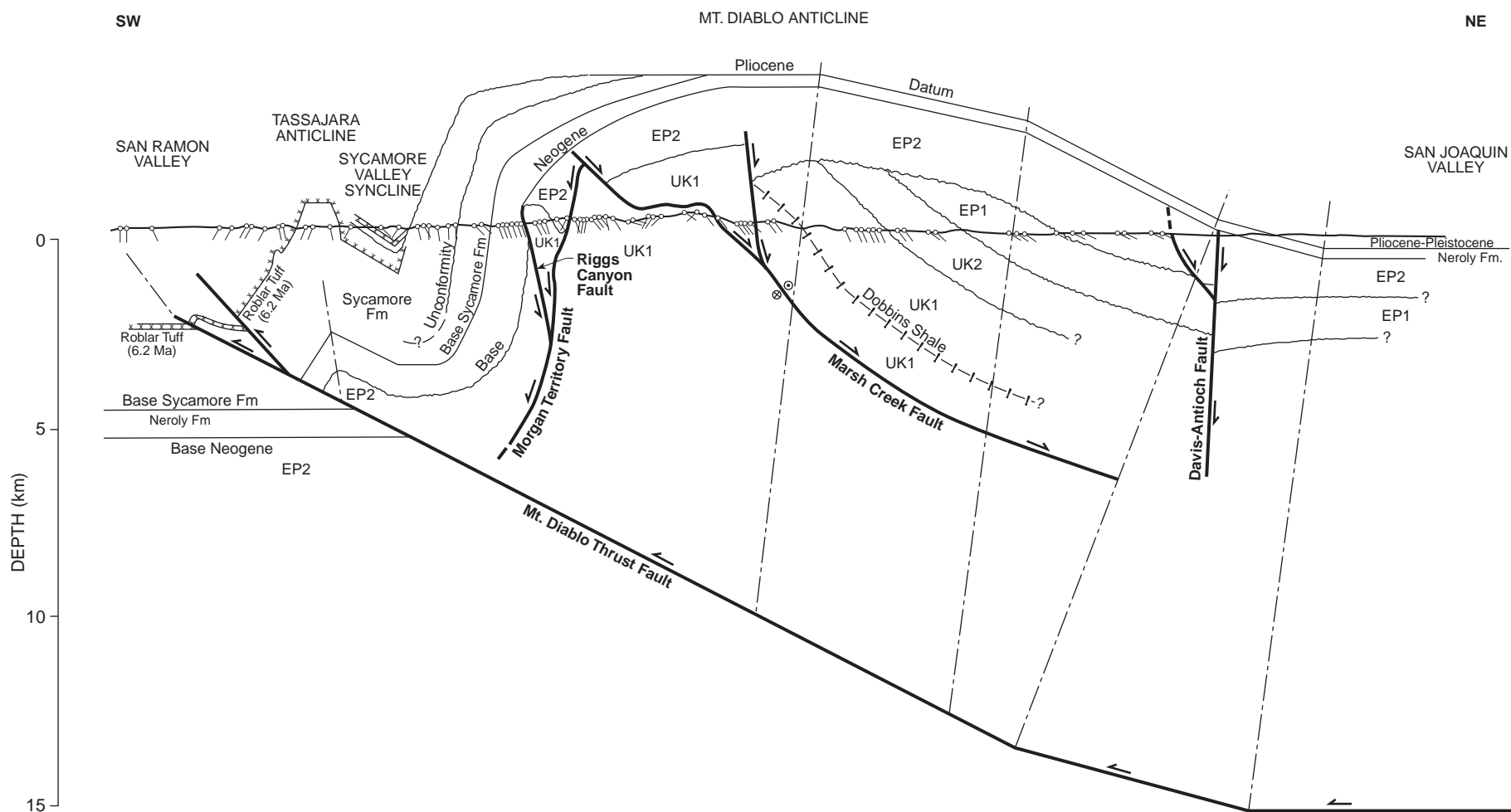
Figure 8. Regional cross-section across Mt. Diablo and Tassajara anticlines (see Figures 1 and 2 for location).

Diablo thrust fault were tested until the folded and restored lengths of the Roblar Tuff marker horizon, the base of the Sycamore Formation, and the base of the Miocene section were equivalent (Figure 9).

Because Mt. Diablo anticline is assumed to have been passively elevated by rigid-body translation of the hanging wall during growth of the Tassajara anticline, the fold was restored to a pre-Tassajara geometry by reducing the absolute elevation of the hangingwall block by about 2 km (Figure 9). The length of the backlimb of Mt. Diablo anticline is reduced by an amount equivalent to the slip on the fault associated with the growth of Tassajara anticline (about 2.7 km; Figure 9). The structure depicted in Figure 9 was a late Neogene-Quaternary fault propagation fold that developed above the blind, northeast-dipping thrust fault.

Map relations and apatite fission-track data also were used to infer the initial geometry of Mt. Diablo anticline. The panel of steeply southwest-dipping to overturned Neogene strata northeast of the axis of the Sycamore Valley syncline was assumed to comprise the forelimb of ancestral Mt. Diablo anticline. The base of the fold forelimb was placed at the axis of the Sycamore Valley syncline, and the top of the forelimb was located near the eastern end of the panel of overturned Miocene beds. Note that the dip of forelimb does not have to be equivalent to the dip of the Miocene strata. Because bedding dips in the late Miocene section generally steepen downward and may reflect southwest-down tilting during deposition prior to folding, the minimum dips of bedding in the Sycamore Formation east of the Sycamore Valley syncline axis (i.e., about 50°) only constrain the *maximum* dip of the fold forelimb. The actual dip of the forelimb may be less than 50° depending on the magnitude of tilting that occurred during basin subsidence, prior to folding.

Maximum structural relief across the initial Mt. Diablo fault-propagation fold was determined by analysis of apatite fission track (AFT) data derived from Eocene and Cretaceous rocks sampled across Mt. Diablo anticline along a traverse near the cross-section line (T. Dumitru, personal and written communication, 1999). The AFT data generally indicate that: (1) The maximum depth of burial of Cretaceous and early Tertiary rocks prior to late Cenozoic uplift and folding was about 3 to 4 km; and (2) there is no significant variation in maximum temperatures experienced by the suite of samples, implying that they all came from about the same paleodepth (T. Dumitru, personal and written communication, 1999). To incorporate these constraints in the reconstruction of the initial Mt. Diablo anticline geometry, an antiformal datum was constructed across the fold that tied exposures of a 4.8 Ma tephra on the backlimb to a flat anticline crest located about 3 to 4 km above the modern levels of exposure sampled for AFT analysis (Figure 9). The southwest limb of the antiform was derived by assuming that the datum dips southwest, coincident with the panel of southwest-dipping Sycamore Formation and Miocene strata east of the Sycamore Valley syncline. As a result, the "4.8 Ma datum" defines a broad, flat-crested anticline with a maximum structural relief of about 3 to 4 km. Although this is not a unique reconstruction of the early fold geometry, it satisfies the outcrop and AFT constraints described above.

Early-stage folding of Mt. Diablo anticline was restored by flattening the derived Pliocene datum. This stage of the restoration explicitly accounts for the effects of flexural simple shear on the geometry of stratigraphic contacts and pre-existing faults in the forelimb and backlimb of the anticline. Typical models of area-balanced fault-propagation folding (i.e., Suppe and Medwedeff, 1990) assume that progressive widening of the fold limbs is accompanied by distributed shearing of strata along planes that are parallel to the fold limbs. In the simplest case, bedding dip is parallel to the dip of the fold limb, and simple shearing of the fold limb is accommodated by bedding-parallel faults. Because contacts and bedding surfaces within the fold limb are parallel to lines of no finite extension in the cross section, there is no change in angular relationships or line lengths within the fold limb during deformation. At Mt. Diablo, however, stratigraphic contacts, bedding
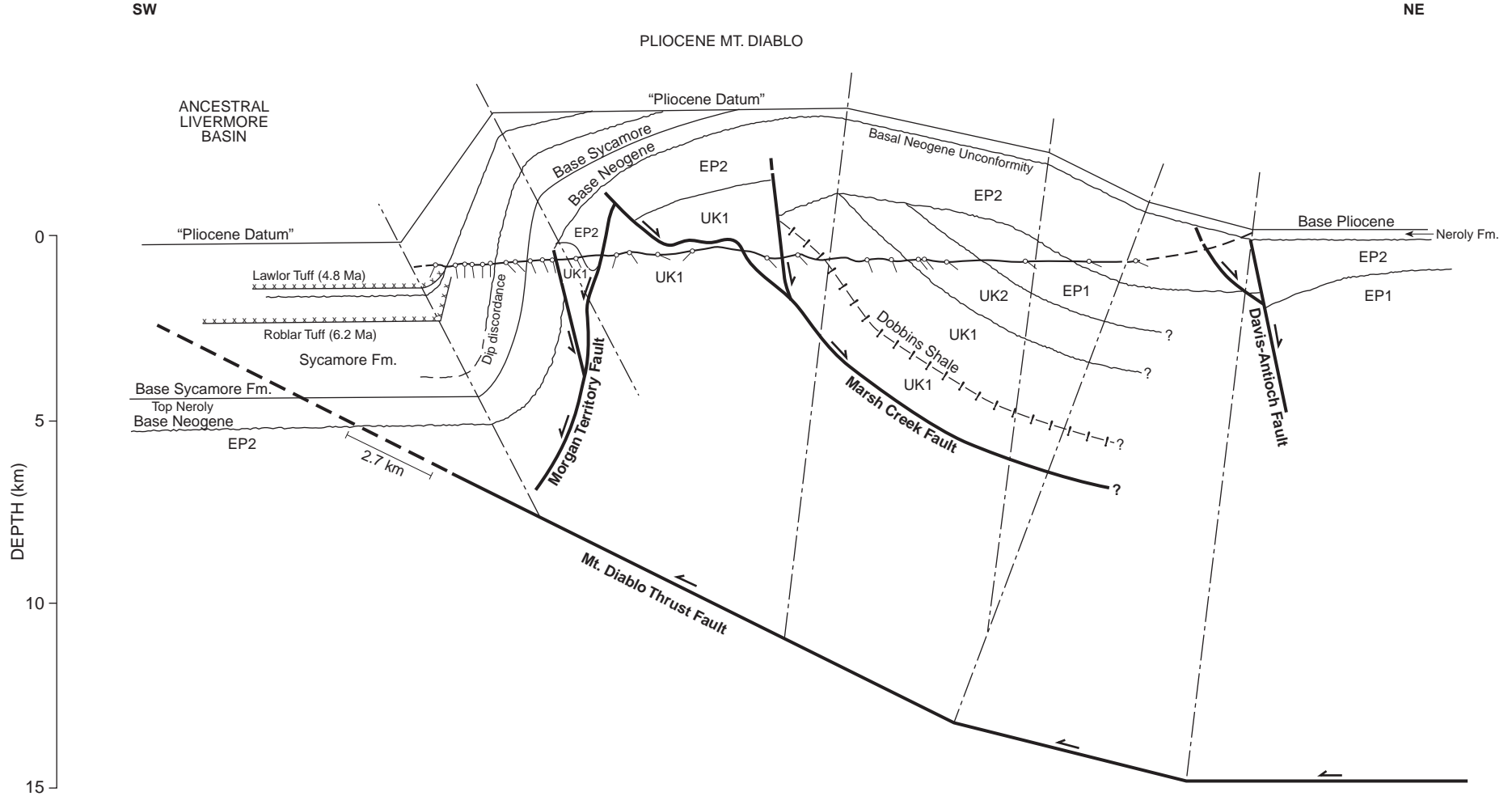
Figure 9. Cross-section in Figure 8 restored by unfolding the Tassajara anticline and removing about 2.7 km of slip on the underlying Mt. Diablo thrust fault. The "Pliocene datum" is a deformed surface representing an originally horizontal plane that connected the base of the Pliocene section on the northeast side of Mt. Diablo with a plane at similar elevation on the southeast side. The plane is constructed so that it presently lies about 3 to 4 km above the modern exposures across the axis of Mt. Diablo anticline, consistent with constraints from apatite fission-track analysis that limit late Cenozoic exhumation of rocks in this region to about 3-4 km. The structural relief on the plane is consistent with the magnitude of slip indicated by the width of dip panels on the backlimb of the fold.

and structural features like faults generally are oblique to the inferred dip of the fold limbs (Figure 9). If the fold limb is progressively deformed by distributed simple shear, then material features within the fold limb will be rotated toward parallelism with the macroscopic shear direction. Angular relationships and line lengths of features within the fold limbs will change with progressive deformation if they are oblique rather than parallel to lines of no finite extension in the plane of the cross section.

The effect of distributed simple shear in the fold limbs was restored by using a graphical approach to map features from the deformed to the restored state. For each cross section, a series of lines was constructed parallel to the inferred dip of the fold limbs. It was assumed that distributed simple shear of the fold limbs occurred parallel to these lines during fold growth, and thus these constructed lines represent lines of no finite extension. The intersections of stratigraphic contacts and faults with these lines formed a grid of points that could be used to transform features in the deformed fold limb to their initial, undeformed state (Figure 10). The distance between these points on a given line of no finite extension is the same in both the deformed and restored states. The lengths and angular relationships of lines that connect these points (i.e., bedding and faults), however, are different in the deformed and restored states due to distributed simple shear of the fold limb. By using the grid of points on (inferred) lines of no finite extension to map stratigraphic contacts and faults to a pre-deformed geometry, area is conserved in the restored cross section and changes in angular relations among material lines are consistent with the assumptions of fault-propagation fold kinematics (Suppe and Medwedeff, 1990).

The restoration in Figure 11 interprets that substantial relief on the base of the Neogene section was present due to late Neogene subsidence of Livermore basin, prior to Plio-Pleistocene folding of Mt. Diablo anticline. To estimate the geometry of the pre-Neogene rocks and structures prior to basin subsidence, the section in Figure 11 was flattened on the basal Neogene unconformity (Figure 12). This restoration was performed graphically and is highly schematic. It is intended to generally illustrate the unconformable relationship between EP-2 strata and the underlying EP-1, UK-2, UK-1 strata, as well as the Franciscan complex.

3.3 Discussion

The restored cross sections imply that there was substantial structural relief on the UK-1, UK-2, and EP-1 packages prior to growth of Mt. Diablo anticline (Figure 11), as well as prior to late Neogene subsidence and filling of Livermore basin (Figure 12). Note that the constraint from the AFT data that the samples represent a similar depth of burial prior to uplift of Mt. Diablo implies that the stratigraphic section including packages UK-1, UK-2, and EP-1 on the northeast limb of the fold dipped to the northeast prior to deposition of the basal Domengine sand in EP-2 time (Figure 11). This relationship is best illustrated by the cross section that restores late Neogene subsidence of Livermore basin (Figure 12). Here, the basal EP-2 strata lap westward on increasingly older and deeper strata, as previously recognized by Moxon (1990) from comparison of stratigraphic columns on opposite limbs of Mt. Diablo anticline. These relations imply uplift and eastward tilting of the fore-arc strata during early Tertiary subduction.

A series of progressively restored cross sections along a traverse through the core of the Mt. Diablo massif (Figures 13, 14, and 15) was constructed using this same approach. The interpretation represented by the cross sections implies a similar history of southwest-side-down tilting along the northeastern margin of Livermore basin between about 11 Ma and middle to late Pliocene, followed by growth of the Mt. Diablo and Tassajara anticlines since 4.8 Ma, and possibly as recently as the 3.3 Ma (the age of the youngest tephra found to date in the Sycamore Formation that are involved in the folding; J. Walker, personal communication, 1999). In the 11 Ma restoration (Figure 15), the Franciscan assemblage structurally underlies the UK and EP
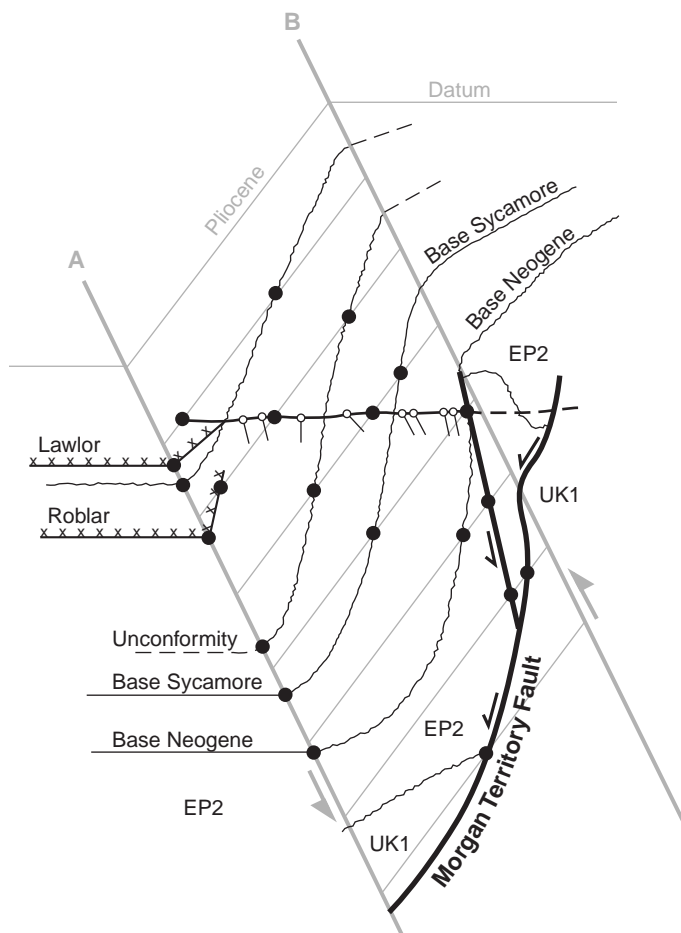
(a) Forelimb of Mt. Diablo Anticline
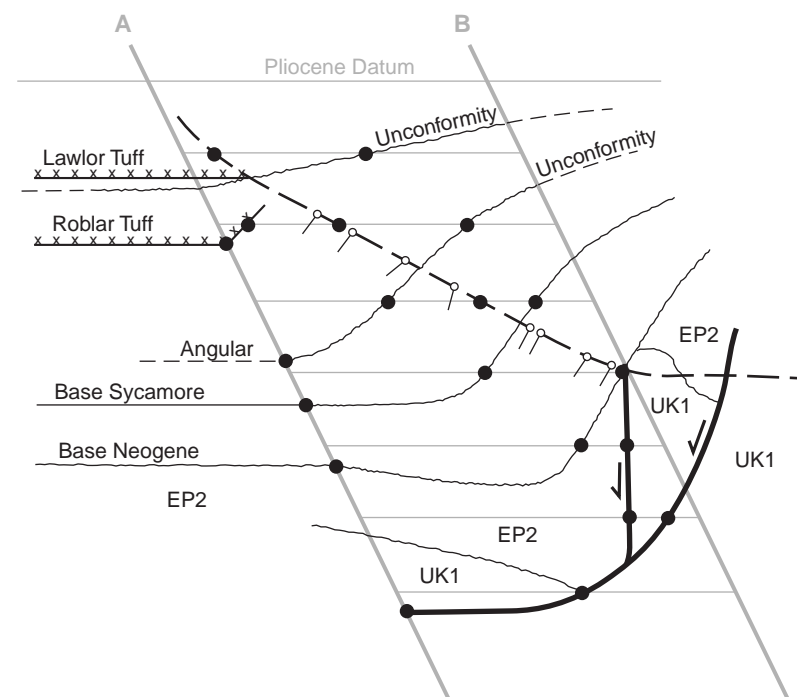
(b) Restored forelimb

Figure 10. Detailed illustration of method used to restore tilted bedding and fault structures in the fold limbs to a pre-deformed geometry. Method assumes that folds grow in a self-similar manner by kink-band migration (Suppe and Medwedeff, 1990). Shearing of fold limbs during deformation is illustrated by comparing geometry of parallelogram defined by the A and B hinge lines in the deformed and restored states. Shear during fold growth is assumed to be accommodated by reverse slip along planes parallel to dip of the fold limb; in general, these planes need not be parallel to bedding. In cross-section, the shear planes are lines of no finite extension. Intersections of bedding, faults and other features with these lines form a grid of points that is used graphically to map the deformed geometry to the restored geometry. See text for additional discussion.

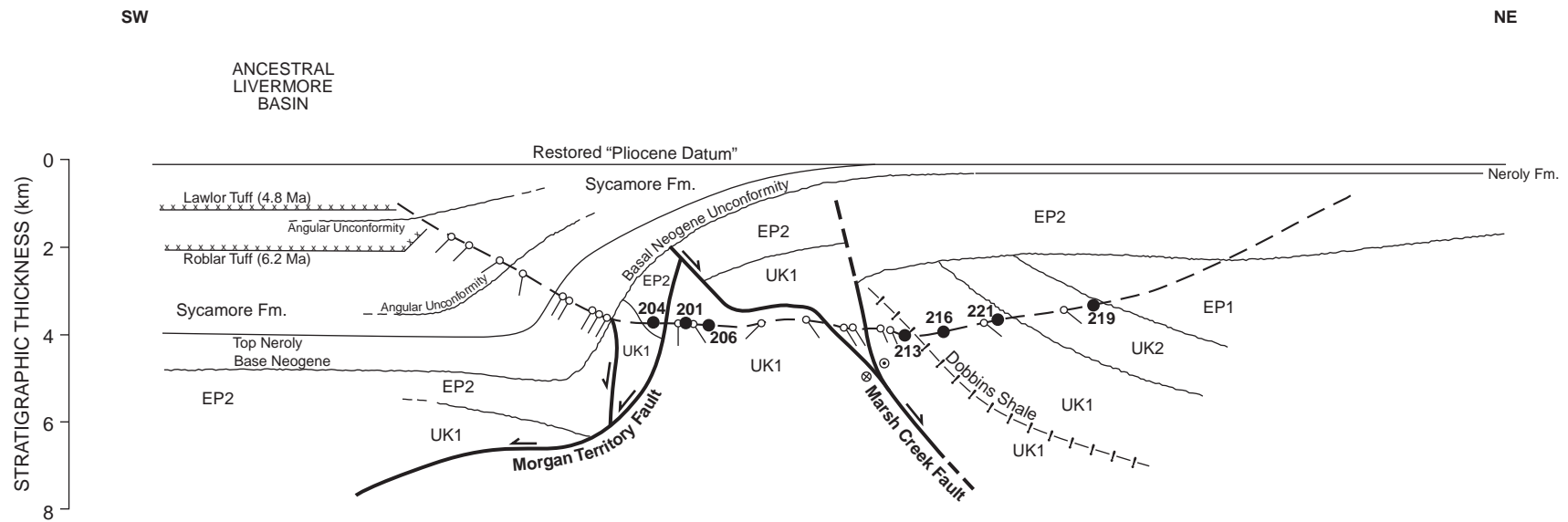Figure 11. Cross-section in Figure 9 restored by unfolding Mt. Diablo anticline and flattening the "Pliocene datum". Concave solid line below "datum" represents the restored modern surface exposure. Note that the restored positions of the AFT sample locations are located at a depth of about 3 to 4 km, and that they all occur at a similar depth; both of these relations are consistent with analysis of AFT data.

Figure 12. Cross-section in Figure 11 approximately restored by graphically removing relief on the basal Neogene unconformity. Resulting section is an interpretation of pre-existing structure in the Mt. Diablo region prior to late Neogene subsidence of Livermore basin. Dashed concave line represents modern surface exposure.

Figure 13. Regional cross-section across Mt. Diablo and Tassajara anticlines (see Figures 1 and 2 for location).
In contrast to Figure 8, this section crosses the Franciscan core of the Mt. Diablo massif.
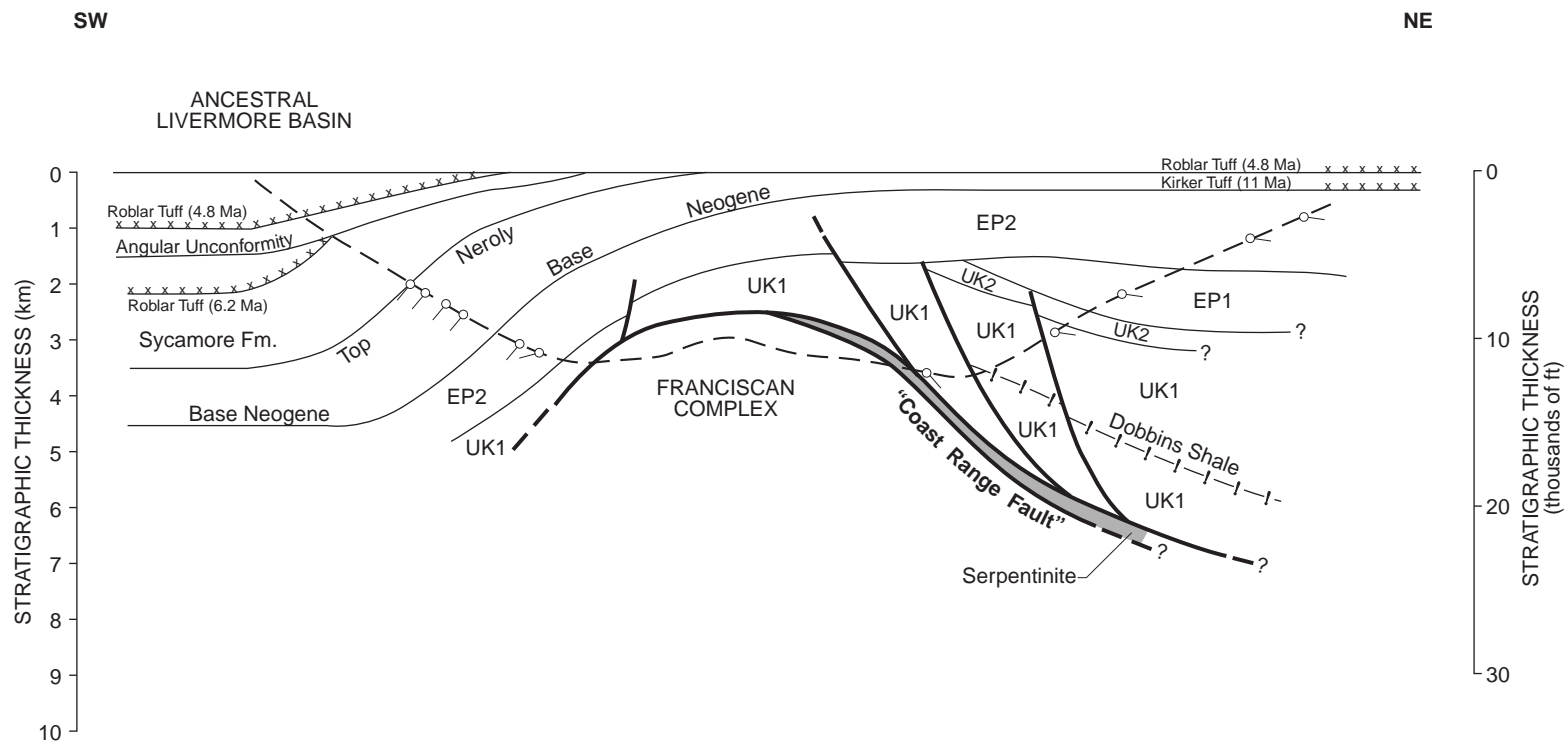
Figure 14. Cross-section in Figure 13 restored by unfolding the Tassajara.and Mt. Diablo anticlines, using the approach illustrated in Figures 9 and 10. Dashed concave line represents modern surface exposure.
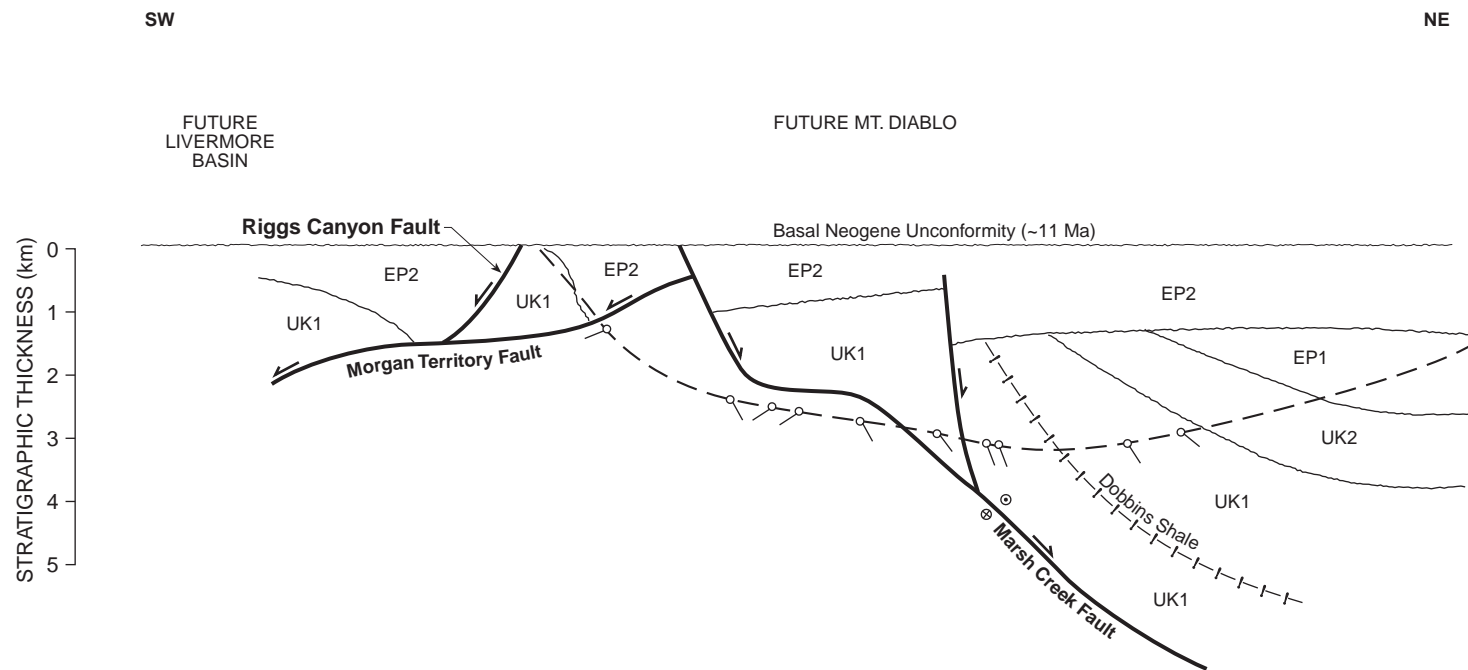
Figure 15. Cross-section in Figure 14 approximately restored by graphically removing relief on the basal Neogene unconformity (similar to Figure 12). Resulting section is an interpretation of pre-existing structure in the Mt. Diablo region prior to late Neogene subsidence of Livermore basin. Dashed concave line represents modern surface exposure.
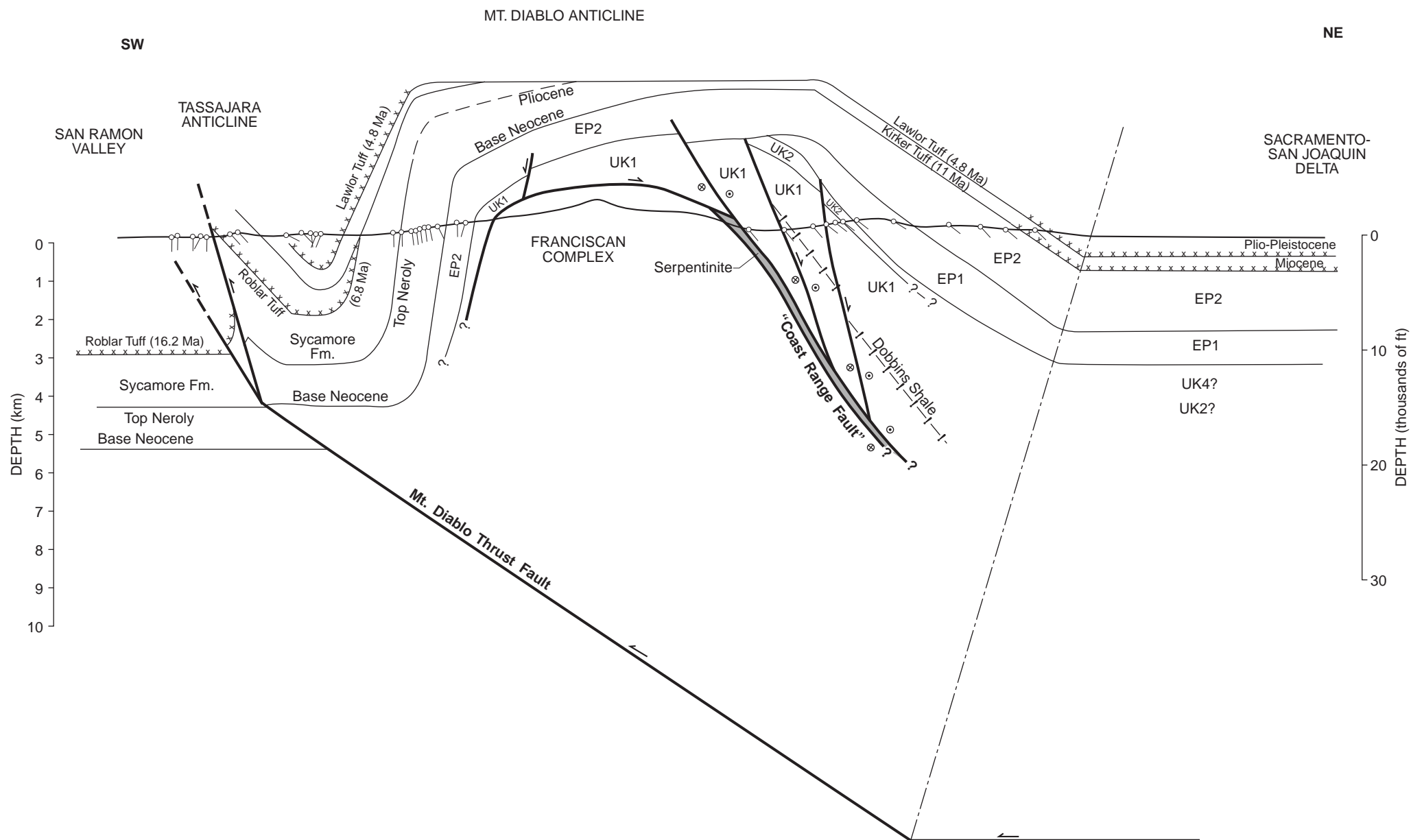
packages of fore-arc strata. The fault or fault zone separating the Franciscan rocks from the overlying fore-arc strata is associated with a thin layer of serpentinite, representing the highly attenuated remnants of the ophiolitic fore-arc basement. Note that the 11 Ma restoration shows EP-2 strata lapping eastward across the Franciscan rocks. This implies that the majority of exhumation of the Franciscan assemblage occurred prior to deposition of the EP-2 package, and is consistent with AFT data which suggest that the Franciscan rocks at Mt. Diablo passed through the apatite annealing temperature at about 60 Ma (i.e., late Paleocene, during EP-1 time; Burke et al., 1997).

Both of the restored cross sections interpret that about 8 km of slip occurred on the blind Mt. Diablo thrust fault to generate the late Cenozoic structural relief and exhumation of the rocks from which the AFT samples were taken. This estimate is less than the maximum late Cenozoic slip inferred by Unruh and Sawyer (1997), because the previous attempt at constructing balanced cross sections did not account for pre-Neogene structural relief on the Cretaceous and Eocene section. The AFT data provide constraints on both maximum depth of burial for these rocks, and variations in pre-uplift burial depth. In particular, the lack of significant variations in maximum burial temperature experienced by the suite of AFT samples implies that they were exhumed from a similar depth (T. Dumitru, personal communication, 1999), and thus collectively define a subhorizontal datum that originally was located at about 3 to 4 km depth (Figure 11). During uplift, this "subhorizontal datum" has not developed detectable relief and thus apparently has not been folded, consistent with the assumption adopted in the balancing approach that the initial Mt. Diablo fault-propagation fold was a broad, flat-crested anticline.

Based on the cross sections developed and discussed in the previous section, maximum late Cenozoic slip on the Mt. Diablo thrust fault is about 8 km. This slip is sufficient to account for uplift of the crustal area of the anticline, and exhumation of the AFT samples. Less slip is required to account for structural relief on the base of EP-2 strata across the northwest-plunging nose of the anticline (Figure 2). If the kinematic model of Unruh and Sawyer (1997) is correct, then some of the distributed NW dextral shear that drives shortening across the restraining Mt. Diablo stepover is transferred to the southern end of the Concord fault, thus reducing total late Cenozoic slip on the Mt. Diablo anticline at this latitude. A maximum of 8 km of slip on the Mt. Diablo thrust fault thus is adopted for the purposes of estimating long-term average slip rate.

At present, the timing of onset of folding must be inferred from stratigraphic relationships. At least some of the growth of the anticline has occurred in the past 3.3 to 4.8 million years, because tephra of this age in the Sycamore Formation are involved in the folding. There is some ambiguity about exactly when folding of the Sycamore Formation began, however, because southwest-down tilting along the margin of the ancestral Livermore basin could be a result of basin subsidence, or folding of the basin margin associated with incipient growth of Mt. Diablo anticline. The simplest interpretation is that growth of Mt. Diablo anticline post-dates deposition of the Sycamore Formation; that is, the deformation post-dates 3.3 Ma. It is unlikely that folding began earlier than 6.2 Ma, because the great thickness of the Sycamore Formation section beneath the 6.2 Ma Roblar tuff is best accounted for by subsidence of Livermore basin, which apparently ceased when growth of Mt. Diablo and Tassajara anticlines began. Using 3.3 Ma and 6.2 Ma to bracket the maximum age of onset of folding, the range of minimum slip rates for the Mt. Diablo thrust fault is about 1.3 to 2.4 mm/yr.

To date, there is no positive geologic evidence to constrain the minimum age for the onset of folding. Sediments as young as the Quaternary Livermore gravels are involved in the deformation, and geomorphic evidence presented by Unruh and Sawyer (1997) and Sawyer (1999) indicates that late Pleistocene and early Holocene geomorphic surfaces in the Tassajara Hills and Livermore Valley are demonstrably folded. If the onset of folding occurred later than 3.3 Ma, then the average slip rate could be higher than 2.4 mm/yr. Sawyer (1999) documented geomorphic evidence for Holocene surface uplift rates of about 3 to 7 mm/yr in the northwestern Tassajara Hills. If uplift of this region is accommodated by rigid body translation of the hanging wall block, then the implied slip rate on the Mt. Diablo thrust fault is greater than the surface uplift rate. These higher rates may reflect local kinematic departures from simple fault-propagation folding (Sawyer, 1999), or they may imply that contractional deformation began later than 3.3 Ma. Additional geomorphic and structural geologic analyses are required to better constrain the late Quaternary uplift rate of the Mt. Diablo and Tassajara anticlines, and thus evaluate the late Quaternary slip rate on the Mt. Diablo thrust fault.

Andersen, D.W., Isaacson, K.A., and Barlock, V.E., 1995, Neogene evolution of the Livermore basin within the California Coast Ranges, in Fritsche, A.E., ed., Cenozoic Paleogeography of the Western United States-II: Pacific Section, Society of Economic Paleontologists and Mineralogists, Book 75, p. 151-161.

Atwater, T., and Stock, J., 1998, Pacific-North America plate tectonics of the Neogene southwestern United States: an update: International Geology Review, v. 40, p. 375-402.

Buising, A.V., and Walker, J.P., 1995, Preliminary palinspastic reconstructions for the greater San Francisco Bay area, 15 Ma-5 Ma, in Sangines, E.M., Andersen, D.W., and Buising, A.V., eds., Recent Geologic Studies in the San Francisco Bay Area: Society of Economic Paleontologists and Mineralogists, Pacific Section Volume 76, p. 141-159.

Burke, J., Burgmann, R., and Dumitru, T., 1997, Uplift of Mt. Diablo using apatite fission tracks and geomorphic analysis: EOS (Transactions, American Geophysical Union), v. 78, no. 46, p. F631.

Crane, R.C., 1995, Geology of the Mt. Diablo region and East Bay hills, in Sangines, E.M., Andersen, D.W., and Buising, A.V., eds., Recent Geologic Studies in the San Francisco Bay Area: Society of Economic Paleontologists and Mineralogists, Pacific Section Volume 76, p. 87-114.

Fox, K.F. Jr., 1983, Tectonic setting of late Miocene, Pliocene, and Pleistocene rocks in part of the Coast Ranges north of San Francisco, California: United States Geological Survey Professional Paper 1239, 33 p.

Graham, S.A., Gavigan, C., McCloy, C., Hitzman, M., Ward, R., and Turner, R., 1983, Basin evolution during the change from convergent to transform continental margin: an example from the Neogene of California, in Cherven, V.B., and Graham, S.A., eds., Geology and Sedimentology of the Southwestern Sacramento Basin and East Bay hills: Field Trip Guidebook, Annual Meeting, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 101-118.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1994, Preliminary geologic map emphasizing bedrock formations in Contra Costa County, California: United States Geological Survey Open-File Report 94-622, 1:75,000 scale.

Ingersoll, R.V., 1978, Paleogeography and paleotectonics of the late Mesozoic forearc basin of northern and central California, in Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States: Pacific Coast Paleography Symposium 2, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 471-482.

Isaacson, K.A., and Andersen, D.W., 1992, Neogene synorogenic sedimentation in the northern Livermore basin, California, in Borchardt, G., Hirschfeld, S.E., Lienkaemper, J.J., McClellen, P., Williams, P.L., and Wong, I.G., eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 113, p. 339-344.

Jayko, A.S., Blake, M.C. Jr., and Harms, T., 1987, Attenuation of the Coast Range ophiolite by extensional faulting, and nature of the Coast Range "thrust": Tectonics, v. 6, p. 475-488.

Krug, E.H., Cherven, V.B., Hatten, C.W., and Roth, J.C., 1992, Subsurface structure in the Montezuma Hills, southwestern Sacramento basin, in Cherven, V.B., and Edmondson, W.F., eds., Structural Geology of the Sacramento Basin: Volume MP-41, Annual

Meeting, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 41-60.

Meltzer, A.S., 1988, Crustal structure and tectonic evolution: central California: Ph.D. dissertation, Rice University, Houston, Texas, 284 p.

Moxon, I. W., 1990, Stratigraphic and structural architecture of the San Joaquin-Sacramento basin: Ph.D. dissertation, Stanford University, California, 371 p.

Nilsen, T.H., and Clarke, S.H. Jr., 1989, Late Cenozoic basin of northern California: Tectonics, v. 8, p. 1137-1158.

Oppenheimer, D.H., and Macgregor-Scott, N., 1992, The seismotectonics of the eastern San Francisco Bay region, in Borchardt, G., Hirschfeld, S.E., Lienkaemper, J.J., McClellen, P., Williams, P.L., and Wong, I.G., eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 113, p. 11-16.

Sarna-Wojcicki, A.M., 1976, Correlation of late Cenozoic tuffs in the central Coast Ranges of California by means of trace element geochemistry: U.S. Geological Survey Professional Paper 972, 30 p.

Sawyer, T.L., 1999, Assessment of contractional deformation rates of the Mt. Diablo fold and thrust belt, eastern San Francisco Bay region, northern California: Final technical report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 98-HQ-GR-1006. 53 p.

Suppe, J., and Medwedeff, D.A., 1990, Geometry and kinematics of fault-propagation folding: Eclogae Geologicae Helvetiae, v. 83, no. 3, p. 409-454.

Unruh, J.R., and Sawyer, T.L., 1995, Late Cenozoic growth of the Mt. Diablo fold-and-thrust belt, central Contra Costa County, California, and implications for transpressional deformation of the northern Diablo Range: American Association of Petroleum Geologists, 1995 Pacific Section Convention Abstracts, p. 47.

Unruh, J.R., and Sawyer, T.L., 1997, Assessment of Blind Seismogenic Sources, Livermore Valley, Eastern San Francisco Bay Region: Final technical report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 1434-95-G-2611, 88 p.

Wagner, D.L., Bortugno, E.J., and McJunkin, R.D., 1990, Geologic Map of the San Francisco-San Jose Quadrangle: California Division of Mines and Geology, scale 1:250,000.

Williams, K.M., 1983, The Mt. Diablo ophiolite, Contra Costa County, California: M.S. thesis, San Jose State University, California, 156 p. plus plates.

Woodward, N.B., Boyer, S.E., and Suppe, J., 1989, Balanced geological cross sections: an essential technique in geological research and exploration: American Geophysical Union Short Course in Geology, Volume 6, 132 p.